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SUMMARY

The YLR99 rocket engine has provided safe operation in the X-15 aircraft and has performed well in flight. Problems encountered in obtaining this performance have significantly affected the X-15 program, however, in terms of manpower and delays, and have required a continuing engine-improvement program to maintain adequate reliability.

The engine development and the problem-correction programs have been extremely time-consuming and have had a significant effect on the engine program. Considerable effort has been expended in obtaining high engine reliability for flight operation. In many problem areas, additional checkout time and operating cycles on the hardware for ground assurance checks have consumed a relatively large portion of the hardware life. Careful balancing of adequate assurance checks with minimum operation of the engine components has provided as much progress in the engine program as many of the product improvement items.

Key factors that have made possible the excellent flight experience of the YLR99 engine are: (1) incorporation of basic design concepts of single-malfunction safety; (2) a rigidly imposed set of maintenance checkout requirements on the ground, including necessary ground firings in the aircraft; (3) pre-launch operations of most of the engine components; and (4) pre-operation and post-operation engine inspections, coupled with checkout requirements.

INTRODUCTION

The inception of the X-15 airplane created the need for a large throttleable rocket engine suitable for use in manned aircraft. Inasmuch as no existing engine could fill the requirement, the YLR99-RM-1 rocket engine was developed specifically for the X-15.

This paper describes the unique operating experience obtained during the first 50 Government flights with the YLR99 engine installed in the X-15 aircraft, with emphasis on problem areas of the engine and their effects on the X-15 program.

Many unusual demands were placed on the YLR99 engine, such as minimum hazard, variable thrust, multiple restart, pre-launch idle, and long life. The complexity of the engine that resulted from these unusual demands made it difficult to obtain high reliability for ground operations. Manned aircraft application of a rocket engine results in the accumulation of a large amount of operating time on operational engines, rather than only on development engines such as in missile applications. This long service life results in problems that might not occur otherwise, or that might be unnoticed.

YLR99 ENGINE

Description

The YLR99 engine is a liquid-propellant powerplant (fig. 1) with the following specifications:

Propellants	
Engine	Liquid oxygen and ammonia
Turbopump	90-percent-hydrogen peroxide
Rated thrust	
Sea level	50,000 pounds
45,000 feet	57,000 pounds
Specific impulse	
Sea level	230 seconds
45,000 feet	265 seconds
Rated chamber pressure	600 psia
Expansion ratio (area)	9.8
Dry weight	910 pounds

The thrust chamber is built on a tubular thrust mount which supports the engine in the aircraft. The injector is mated directly to the thrust chamber and carries a two-stage igniter in a counterbore in its forward end. The engine valving and other controls are bracketed to the chamber and injector, and only the valving controlling the hydrogen-peroxide (H_2O_2) requires separate support. The hydrogen-peroxide components are carried in a removable section of the X-15 engine-compartment firewall which is assembled with the engine. With this minor exception, the engine is a completely self-contained package that requires only service, control, and propellant connections to provide full propulsive power.

The five principal modes of engine operation are (1) turbopump idle, (2) igniter idle, (3) fire (main chamber operation), (4) shutdown, and (5) restart. The turbopump-idle mode provides for operation of the turbopump without operating the igniters or thrust chamber. Igniter-idle operation allows checkout of more than 90 percent of the moving components of the engine before the airplane is committed to free flight. The restart capability makes it possible to restart the engine as many as five times with the X-15 pneumatic system. To date, the X-15 program has not required engine shutdown and restart; however, the capability may be used in future programs. The engine has been restarted successfully after launch on three occasions when a postlaunch shutdown was initiated by the engine malfunction-protection system.

History of Engine Development

Early in the X-15 engine development program, it was apparent that there would be considerable delay in obtaining a flight-rated engine. Thus, LR11 engines were used in two of the airplanes until the YLR99 engines became available about a year later. With the interim engine, the airplane was capable of a Mach number of about 3.5; consequently, a portion of the planned flight program was accomplished with this engine. In September 1958, it was necessary to freeze the design of the YLR99 engine with the reduced performance shown in the following table:

	Initial proposal, Feb. 1956	Initial contract, June 1958	First flight engine, Mar. 1961	Improved flight engine, Sept. 1962
Maximum thrust at 45,000 feet, lb	57,000	57,000	57,000	57,000
Minimum thrust at 45,000 feet, lb	19,500	19,500	31,500	19,500
Specific impulse at sea level, sec	241	238	230	230
Specific impulse at 45,000 feet, sec	278	272	265	265
Engine weight, dry, lb	540	856	910	910
Engine weight, wet, lb	625	990	1,025	1,025

In addition to the reduction in specific impulse, the weight was increased significantly and the throttle range reduced. Development tests were later completed to return the minimum thrust to the 19,500-pound level (45,000 feet). Incorporation of this thrust capability into flight engines has been completed; however, engine operation is limited to about 27,000 pounds of thrust because of the high vibration levels encountered at lower thrusts. The reductions in specific impulse and throttle range and the increase in weight have not materially affected the X-15 flight program, inasmuch as the program was conducted on the basis of the available performance.

A long and troubled development period was necessary to attain the engine's present state of reliability. Four development test stands were used by the manufacturer, and a fifth was constructed at Edwards Air Force Base for final acceptance testing. Two of the manufacturer's test stands were of the battleship type, one was a component stand, and one had flight-vehicle-type propellant tanks and lines. This stand could also simulate aircraft attitudes. The stand at Edwards Air Force Base also incorporates flight-vehicle-type components. During the development period, more than 500 minutes of engine operation and over 640 starts were accumulated on 14 engines, utilizing 3 of the manufacturer's stands. These tests were in addition to the component tests performed on the static test stand at Edwards for engine checkout and later development work. The first complete flight-configured engine was fired in February 1958, the preliminary flight rating test (PFRT) was completed in January 1960, and the engine was first used in flight in November 1960.

Instrumentation

During flight, 20 engine parameters are telemetered and monitored in real time by ground engineers to back up and supplement the pilot's cockpit presentation. In addition, 14 parameters are recorded on board to provide more accurate data than given by the telemetry system. The onboard system is the primary source of data for monitoring the automatic shutdown control system and for determining the source of a malfunction. The following table lists the parameters measured and the monitoring method:

Parameter	Onboard recorder	Telemetry	Cockpit
Helium source pressure (fuel–oxidizer) pressurization		✓	✓
Helium source pressure (control No. 1)		✓	✓
Helium source pressure (control No. 2)		✓	✓
Liquid-oxygen tank pressure	✓	✓	✓
Ammonia tank pressure	✓	✓	✓
Liquid-oxygen line pressure	✓	✓	✓
Ammonia pump inlet pressure	✓	✓	✓
Engine purge pressure		✓	
Ammonia turbopump pressure	✓	✓	✓
Liquid-oxygen turbopump pressure	✓	✓	✓
Control gas (regulated)		✓	✓
First-stage igniter pressure	✓	✓	
Second-stage igniter pressure	✓	✓	✓
Main chamber pressure	✓	✓	✓

Parameter	Onboard recorder	Telemetry	Cockpit
Liquid-oxygen injector			✓
Ammonia injector			✓
Propellant pump speed	✓	✓	
Engine sequence	✓	✓	
Engine malfunction	✓	✓	
Engine firing	✓	✓	
Liquid-oxygen pump bearing temperature		✓	
Governor outlet hydraulic pressure	✓		
Auxiliary purge pressure		✓	

Maintenance

The major maintenance and overhaul of the engine is the responsibility of the U.S. Air Force. NASA, the operating agency, is concerned primarily with minor maintenance and modifications, which are performed as necessary to keep an engine in flight status.

When major maintenance becomes necessary on an operational engine, the engine is sent to the Air Force propulsion systems test stand shop at Edwards. When the maintenance is completed, the engine is test fired (fig. 2) and returned to NASA. The engine is then installed in the aircraft and test fired again (fig. 3). If found to be in satisfactory condition, it is used for flight.

Checkout of most of the electrical control system, lubrication and hydraulic system servicing, and preflight inspection are performed within 3 days of a given flight and repeated if necessary to maintain this period of proximity to the flight.

Leak checks of hydraulic lubrication, propellant, and pneumatic systems are performed before every operation. Ground test firings of the engine while in the airplane are made at a minimum interval of every other flight.

ENGINE OPERATIONAL PROBLEMS

A significant number of operational problems had to be overcome in order to bring the YLR99 engine to its present state of reliability and to conduct the X-15 flight program. Many of the problems, such as seal and gasket failures, were of the types that might be expected with the use of cryogenic and corrosive fluids. Other problems arose as a result of the unexpected number of ground operations that have been required. A general discussion of the more serious problems is presented in the following sections.

Control Box

The control box is the electronic heart of the engine and is responsible for engine control and sequencing. The major problem encountered was the failur of pressure switches as a result of ammonia corrosion of the silver contacts. This problem was eliminated by the use of gold contacts. Minor problems include wiring discrepancies, servoamplifier failures, and timer failures. The original design of the control box did not provide for recording the source of a malfunction signal. This valuable aid for trouble-shooting was incorporated during the flight program to provide sequence readout of each malfunction source signal.

Igniter

The igniter used in the YLR99 engine is a two-stage unit providing an ignition source for the main chamber. Three spark plugs in the first stage initiate the combustion process. Explosions in the igniter at the time of engine shutdown have been a significant problem (ref. 1). The explosions have occurred onl during what is referred to as a "lox depletion shutdown," that is, the engine shuts down automatically when the liquid-oxygen tank empties before the fuel in the ammonia tank is depleted. Such shutdowns did not occur during the early X-1 flights. For these flights, the full capacity of the propellant tanks was not needed, and engine shutdown was the result of pilot action. The explosions were presumably, the result of reverse flow which permitted unburned ammonia to pass from the combustion chamber into the oxygen manifold of the second-stage igniter where it mixed with residual oxygen and subsequently detonated. Figures 4(a) and 4(b) show the damage that resulted from such explosions.

In order to operate around the igniter-explosion problem, pending a solution, the X-15 was programed only for fuel-depletion shutdowns to prevent any further igniter damage. An auxiliary purge system is being installed as a permanent solution. This system consists of a regulated helium supply which pressurizes the igniter liquid-oxygen supply system when liquid-oxygen pump discharge pressure decays.

Similar, but less damaging, pressure excursions have occurred in combustior pressure-sensing lines leading to instrument transducers. These detonations occur frequently in the second-stage igniter-chamber pressure-sensing line durir thrust decreases and are caused by the entrance of unburned combustible gas during the previous increasing-pressure cycle. It is not feasible to move the pressure pickup point, and no other means of correction has been found.

The igniter is also a factor in engine-combustion vibration problems. In ε few instances, replacing the igniter relieved the problem. Certain combinations of components, although individually acceptable, may be incompatible as a unit. The condition has been termed "vibration incompatibility."

Hydrogen-Peroxide System

The major difficulty with the YLR99 hydrogen-peroxide system has been metering-valve "sticking." This problem has been corrected by increasing the clearance between the cylindrical valve and the sleeve assembly.

Other problems have been catalyst-bed deterioration, seal leakage, and corrosion. Substitution of electrolytically produced hydrogen-peroxide has solved the problem of catalyst-bed deterioration. (The engine was qualified only for electrolytic hydrogen-peroxide.) Solutions to the seal leakage and corrosion have not been found.

Oxidizer System

The major difficulties in the oxidizer system have been main-propellant-valve leakage and the inability to adjust the oxidizer-fuel ratio (O/F) without removing the engine from the aircraft.

Improved lip and shaft seals have aided in solving the problem of main-propellant-valve leakage, and an improved valve is being demonstrated. Inasmuch as ambient pressure affects the engine O/F ratio (because of the resultant change in liquid-oxygen temperature), an orifice adjustment must be made between ground and flight operations if a constant O/F ratio is to be maintained. Initially, the adjustments could be made only with the engine removed from the airplane. An engine must be operated after installation to qualify for flight; therefore, many ground runs were made with flight orifices and, as such, at "off-design" O/F ratio. A quick-change orifice was designed and incorporated that made it possible to adjust the O/F ratio with the engine installed in the airplane.

As a result of a series of igniter explosions, several of the flight engines were disassembled to remove all traces of suspected incompatible lubricant in the oxidizer system. This cleaning was done in the belief that the lubricant was impact-sensitive and responsible for the second-stage igniter explosions. It was shown later that the lubricant was not the cause of the explosions, even though it was found to be out of specification for impact sensitivity.

Helium System

The engine helium system uses gas for actuation of the propellant valves and purging of the propellant system. No major problems have been encountered with the helium system. Minor problems have included leakage from quadruple check valves, solenoid vent seats, and control gas valves. Also of interest was the unseating of purge orifices when the original pressed fit was being used. Initially, it was believed that "staking" the edges of the recess after inserting the orifices would solve the problem; however, this action proved unsatisfactory. A machined orifice fitting is now being used.

Turbopump

The engine propellant turbopump provides propellants at the high pressures required for proper engine operation. Steam and propellant leaks and corrosion have been problems with the turbopump. Leak checks of the turbopump are made with nitrogen gas. Through experience, it has become possible to accurately interpret variations caused by thermal expansion and, thus, to write new specifications on the amount of acceptable nitrogen leakage. Dielectric corrosion of the fuel case—turbine case mating surfaces is being studied. The principal solution being considered is the use of aluminum instead of magnesium in fuel-case fabrication.

Electrical System

Spark-plug life has been the greatest problem in the electrical system. The engine manufacturer is engaged in a spark-plug life-improvement program. Minor problems have been faulty cabling, governor actuator failure, vibration cutoff reliability, and valve limit-switch failures.

Chamber and Injector

Coolant leaks into the thrust chamber have been of concern, inasmuch as they result in rejection of the engine and require major maintenance. Such leaks usually occur as a result of thrust-chamber ceramic coating loss, with the subsequent nitrogen embrittlement and cracking of the chamber tubes. Use of improved coatings has partially relieved this problem and increased chamber life. Thrust-chamber coating loss due to vibration has been, and continues to be, a major problem. NASA Flight Research Center personnel developed a machine which makes it possible to recoat the combustion chamber walls without removing the injector head which is welded into place. The machine is in use at Edwards, thus keeping maintenance time to a minimum.

Cracks in the injector shower heads caused by vibration have presented another problem, in that such cracks could lead to mixing of propellants and rejection of the injector.

Hydraulic System

The hydraulic system is used to position the hydrogen-peroxide metering valve, thereby controlling the flow of hydrogen-peroxide to the gas generator. Problems encountered in this system included porous governor castings, which were corrected by tighter quality control; difficulty in servicing the hydraulic system, overcome by incorporating a bleed screw in the metering valve; and corrosion, corrected by the use of an inhibitor.

Fuel System

Improvement of the main propellant valve (see Oxidizer System discussion) was the major fuel-system problem. Another problem was the modification of the "banjo joint seal" to provide easier O-ring replacements.

Lubrication System

The lubrication system supplies oil to the turbopump bearings. Early in the program, cavitation of the lubrication pump was responsible for several engine shutdowns through the lube-pump pressure-switch malfunction circuitry. It was determined that the cavitation was caused by acceleration forces on the accumulator and pump. The problem was alleviated by installing a timer to prevent engine shutdowns by oil-pressure fluctuations. These fluctuations were too short in duration to damage the bearings. Another modification was the relocation of a fitting to improve governor accessibility. A proposal has been made to eliminate this system by using packed and liquid-oxygen-lubricated bearings.

Mechanical Arrangement

The engine prime overboard lines were relocated early in the flight program as a result of captive-flight airflow conditions which caused propellants to enter the thrust chamber during prime. Other problems were transducer relocation, fitting durability, and quick-disconnect relocation. Also, a study was made to replace lock-wiring, but no suitable device was found for this engine. To provide for less wear and better sealing of AN tube fittings, conical lip seals were used. Much of the tubing on the engine is welded or specially contoured, thus fitting wear during disassembly and assembly must be avoided.

DISCUSSION

The relative proportions of X-15 flight delays from various causes are illustrated in figure 5. As shown, the YLR99 rocket engine caused more delays than any other single factor except weather. In the few instances in which two problems occurred, either of which would cause a delay, both are included. The miscellaneous bar accounts for problems of less than 2-percent frequency.

The time that elapsed from the recognition of major engine problems until implementation of the correction is shown in figure 6. The figure includes X-15 project office consideration, the manufacturer's study, development, and fabrication, and the component installation. It is evident that much time was involved in problem correction, and that several of the most serious problems were found relatively late in the engine program. Most of the indicated problems were circumvented, however, until a satisfactory solution was found.

Figure 7 indicates the systems responsible for repeated operations, that is, additional operations required to qualify an engine for aircraft installation or flight when the initial qualification run was unsuccessful. Included are instances when failure to qualify resulted in removal of the engine from the aircraft. As shown, the H_2O_2 system was the cause of nearly 30 percent of the total repeated operations. The thrust chamber and turbopump also caused a large percentage of repeated operations.

The service life of each flight engine and of the individual components is shown in figure 8(a) and figure 8(b), respectively. Theoretically, there is no difference in the operational reliability of the available engines, but engine operations per successful flight average from 3.6 to 47 for the various engines, with an overall average of 5 operations per flight. Removal of major components is significant in that a large amount of disassembly, checkout, and reassembly time is required to accomplish the chamber or turbopump changes, thus adding greatly to the effort required to maintain the engines. Information on engine S/N 105 is limited, since the engine was damaged beyond repair early in the program by an explosion in the X-15-3 airplane.

Engine operation time during the program is summarized in figure 9, which presents a graphical comparison of operating time accrued on flight engines. As shown, actual flight time accounts for less than one-third of the total time. Contractor time consists of development and demonstration firings.

Figure 10 is a summary of the various types of operations in the engine program. Aborts refer to instances when the mission is cut short because of a malfunction. A prelaunch abort consists of returning to Edwards with the X-15 still attached to the B-52. A postlaunch abort requires an emergency landing at a dry lake near the launch area. The one postlaunch abort that has occurred was caused by a pressure-switch failure at launch. Engine removals are significant in that the flight schedule is often delayed because of the time involved in changing engines and the availability of operational engines. The average of nearly 1 engine removal per flight indicates that the possibility of replacement engines remaining operational for several flights is low.

The progress made during the flight program in obtaining engine reliability is shown in the following table:

Operation	Aircraft contractor	Consecutive YLR99 engine Government flights				
	3 flights	1 to 10	11 to 20	21 to 30	31 to 40	41 to 50
Engine operations per launched flight	5.7	4.5	4.2	2.4	2.2	2.5
Engine time per launched flight, minutes	15	8.7	4.6	2.6	2.9	2.1
Engine removals per launched flight	2	1.0	1.7	1.0	0.3	0.8
Attempted turn-around flights	---	0	1	4	2	3
Successful turn-around flights	---	0	0	4	2	3
Percentage of unsuccessful ground runs (runs repeated because of engine problems)	---	52	47	55	39	33

Most of the items listed have improved significantly, but the present ground-run reliability of only 33 percent requires improvement. "Turn-around flight" refers to two consecutive flights made without an intervening ground run. This operation is attempted only when satisfactory operation is obtained on the previous flight, and a ground run must be performed after each turn-around flight. This practice eliminates many engine operations and increases hardware life.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., May 4, 1964.

REFERENCE

1. Row, Perry V., and Fischel, Jack: X-15 Flight-Test Experience. Astronautics and Aerospace Eng., vol. 1, no. 5, June 1963, pp. 25-32.

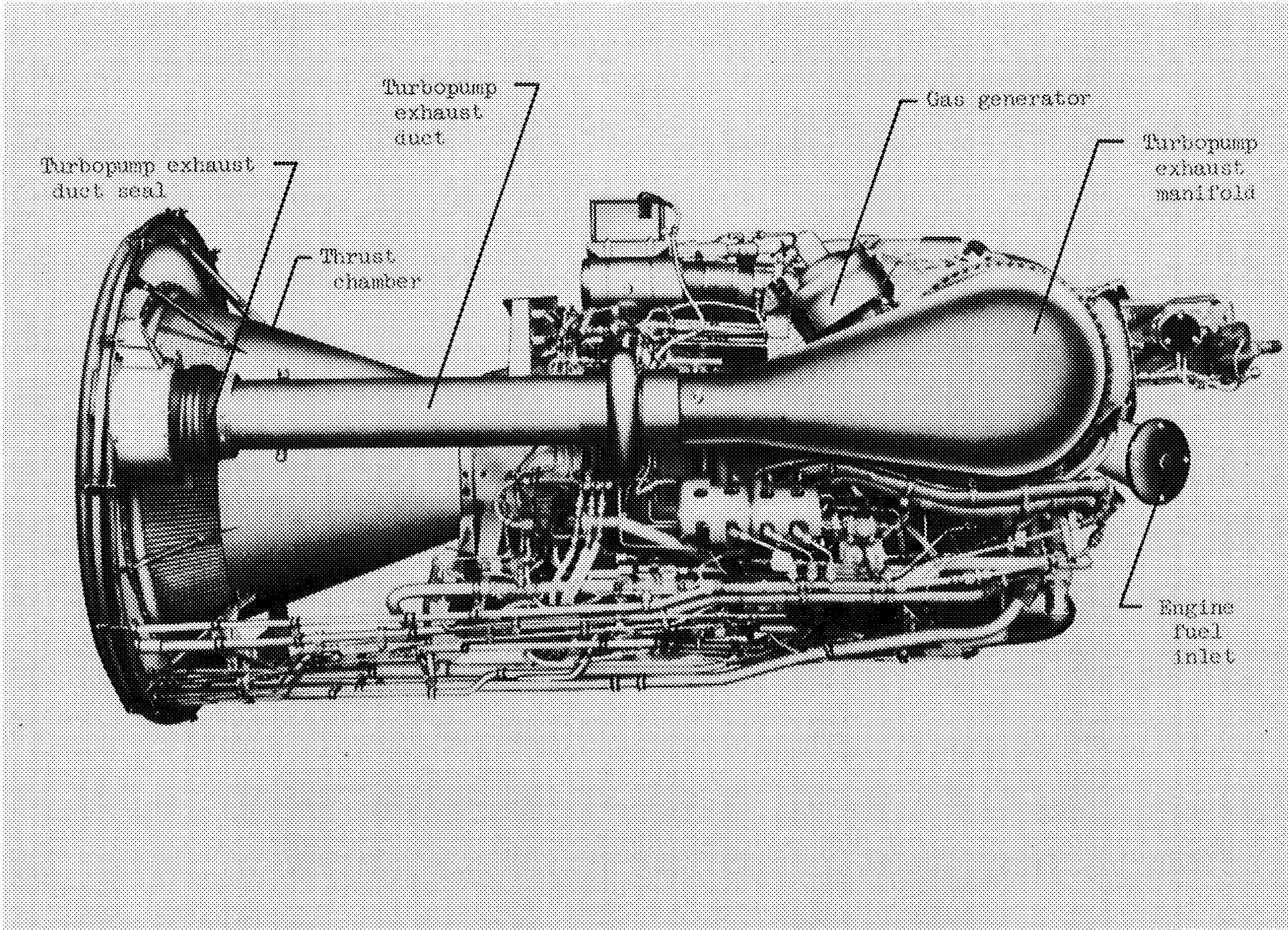


Figure 1.- YLR99 liquid-propellant rocket engine.

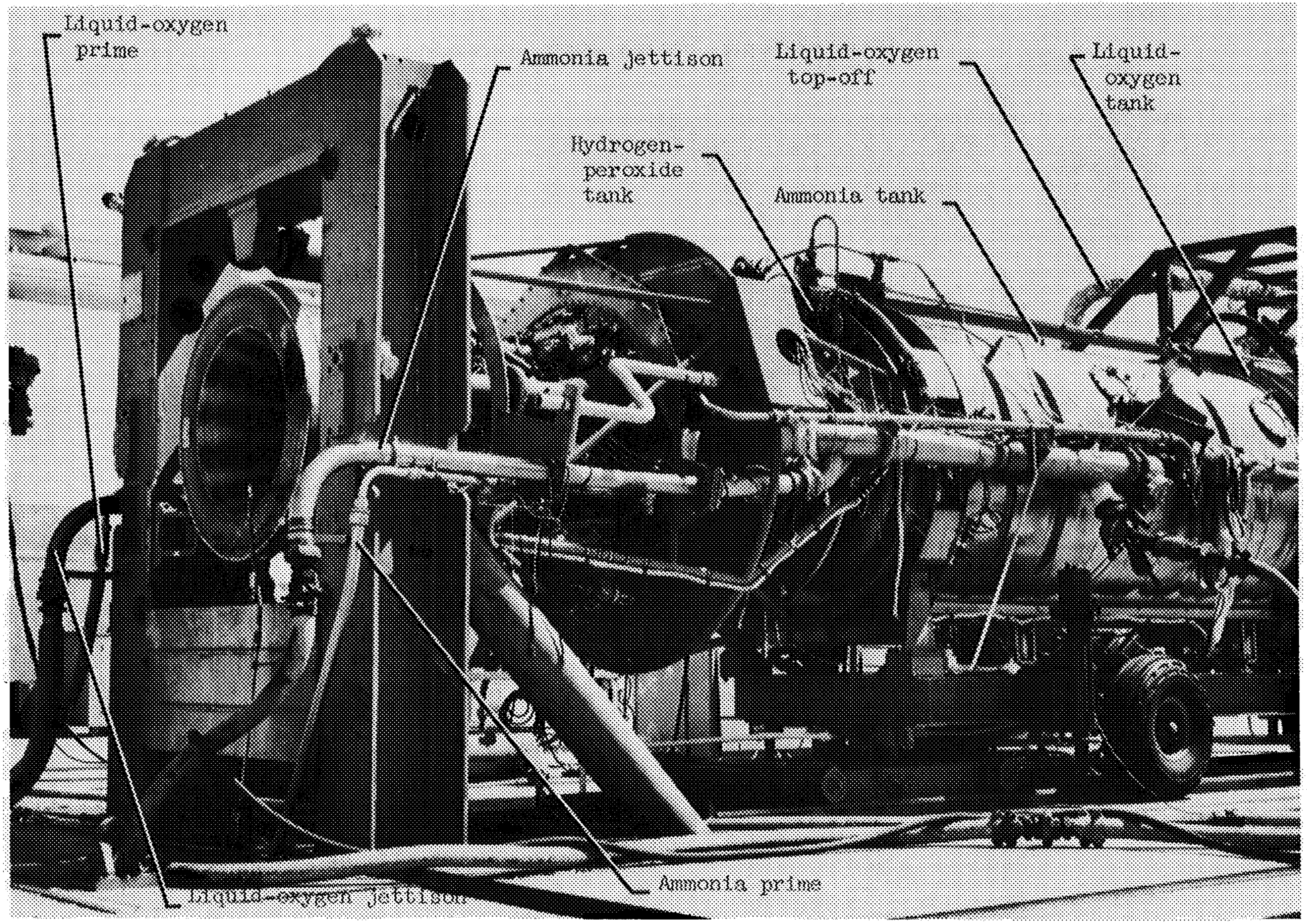


Figure 2.- YLR99 engine installed in the Air Force propulsion systems test stand.

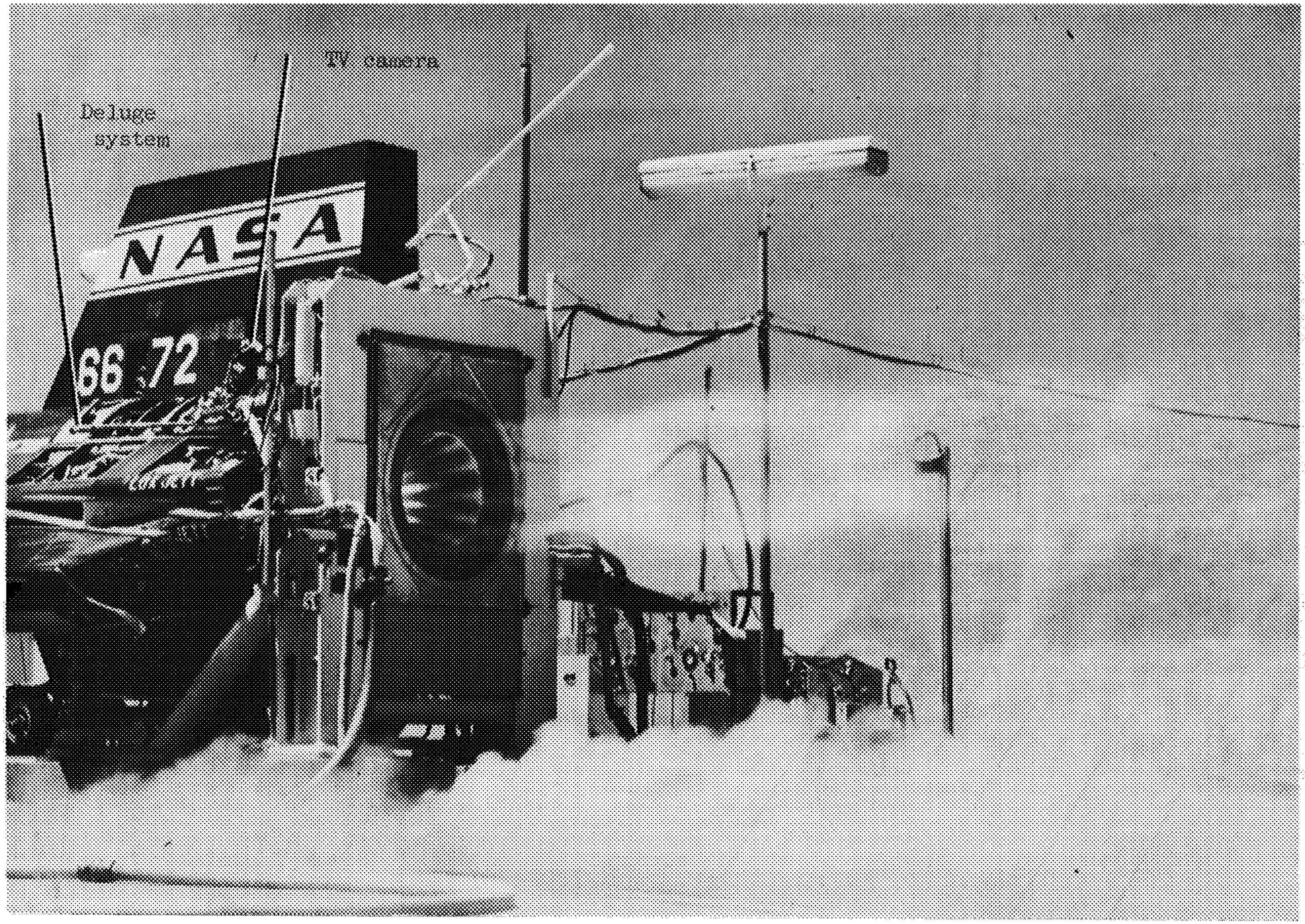
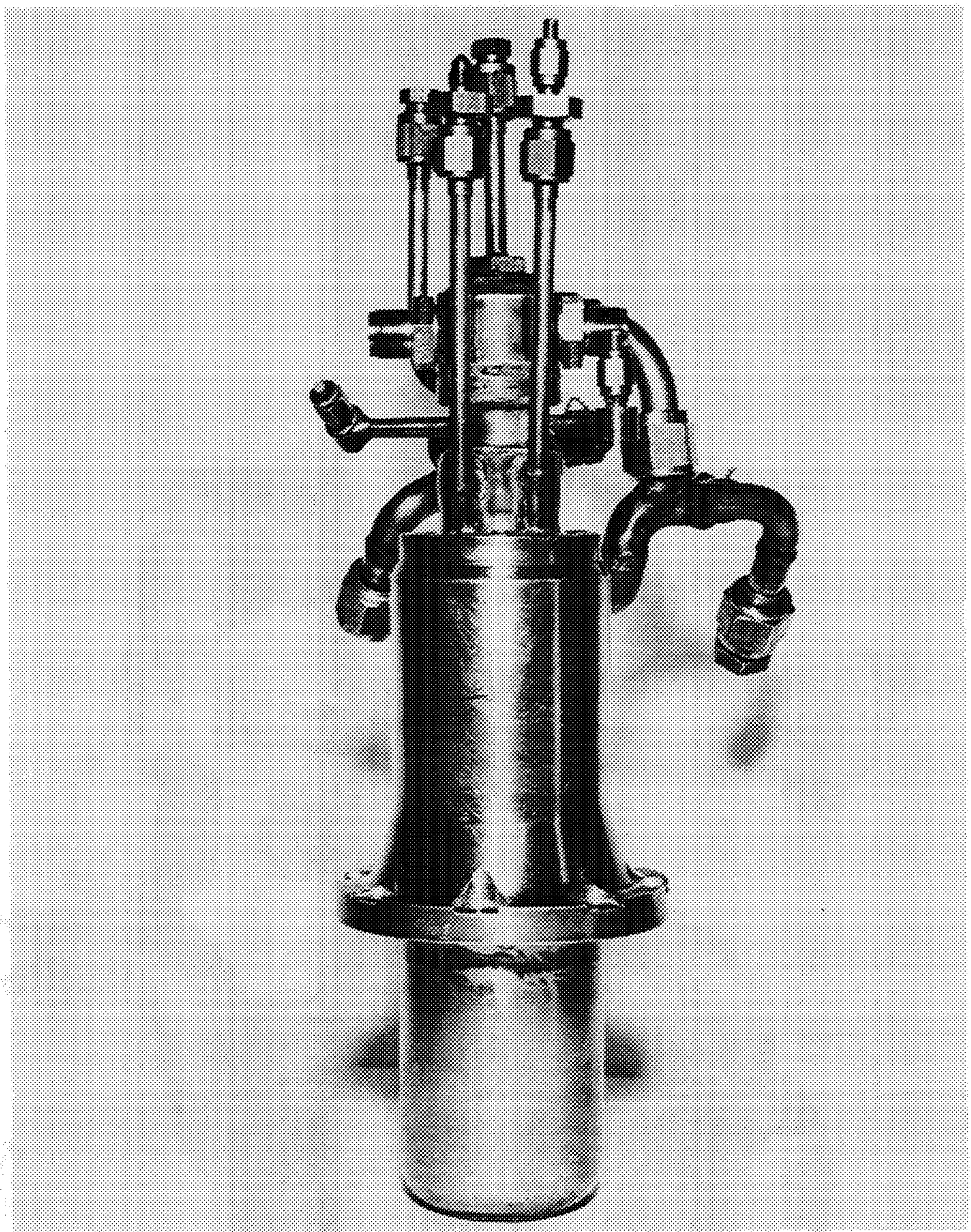
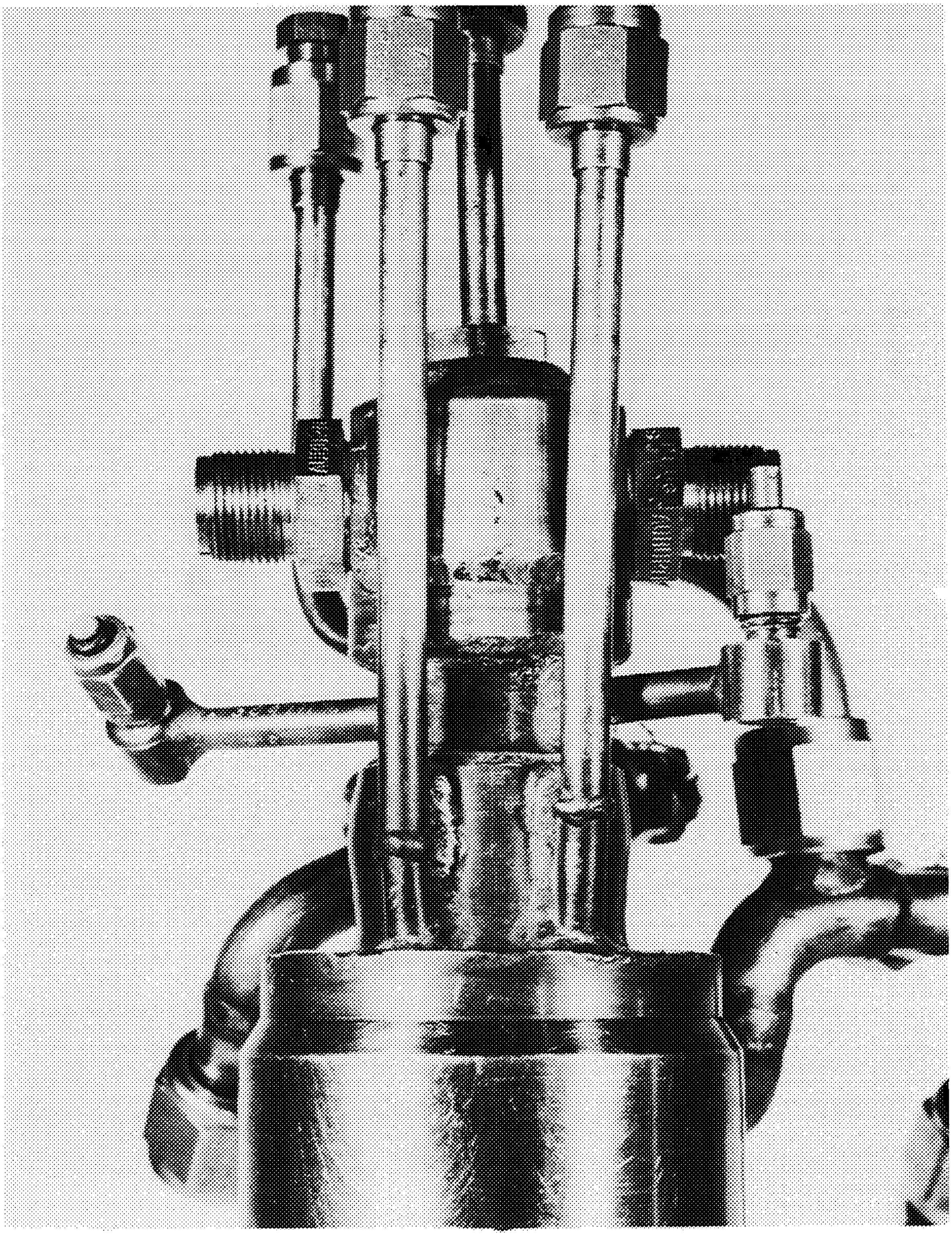


Figure 3.- YLR99 engine firing in X-15.



(a) General view.

Figure 4.- Photographs of damaged igniter.



(b) Closeup showing bulged cooling-jacket wall.

Figure 4.- Concluded.

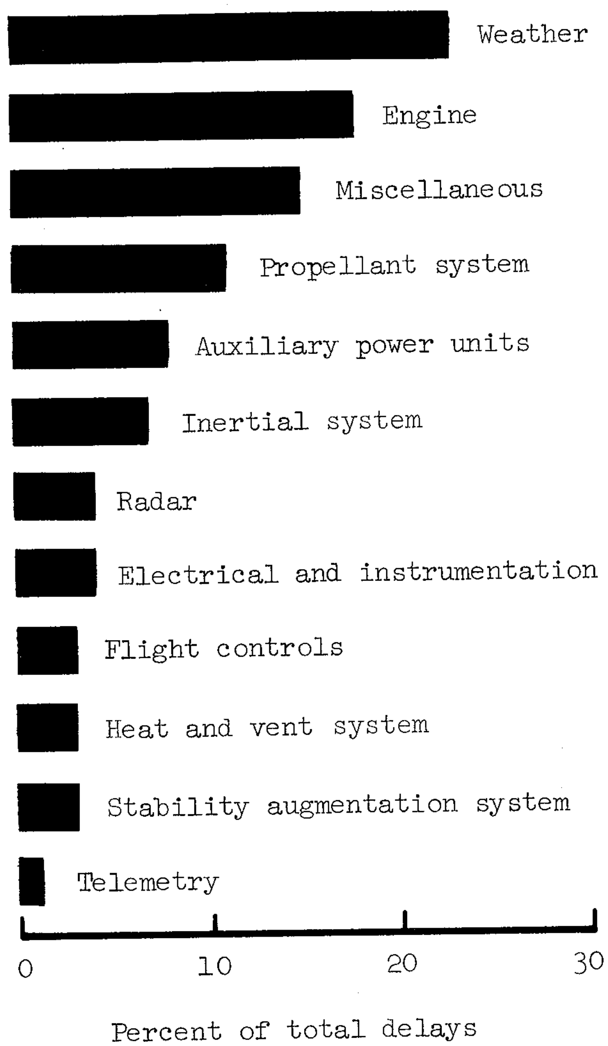


Figure 5.- Sources of flight cancellations during the first 50 Government flights with the YLR99 engine.

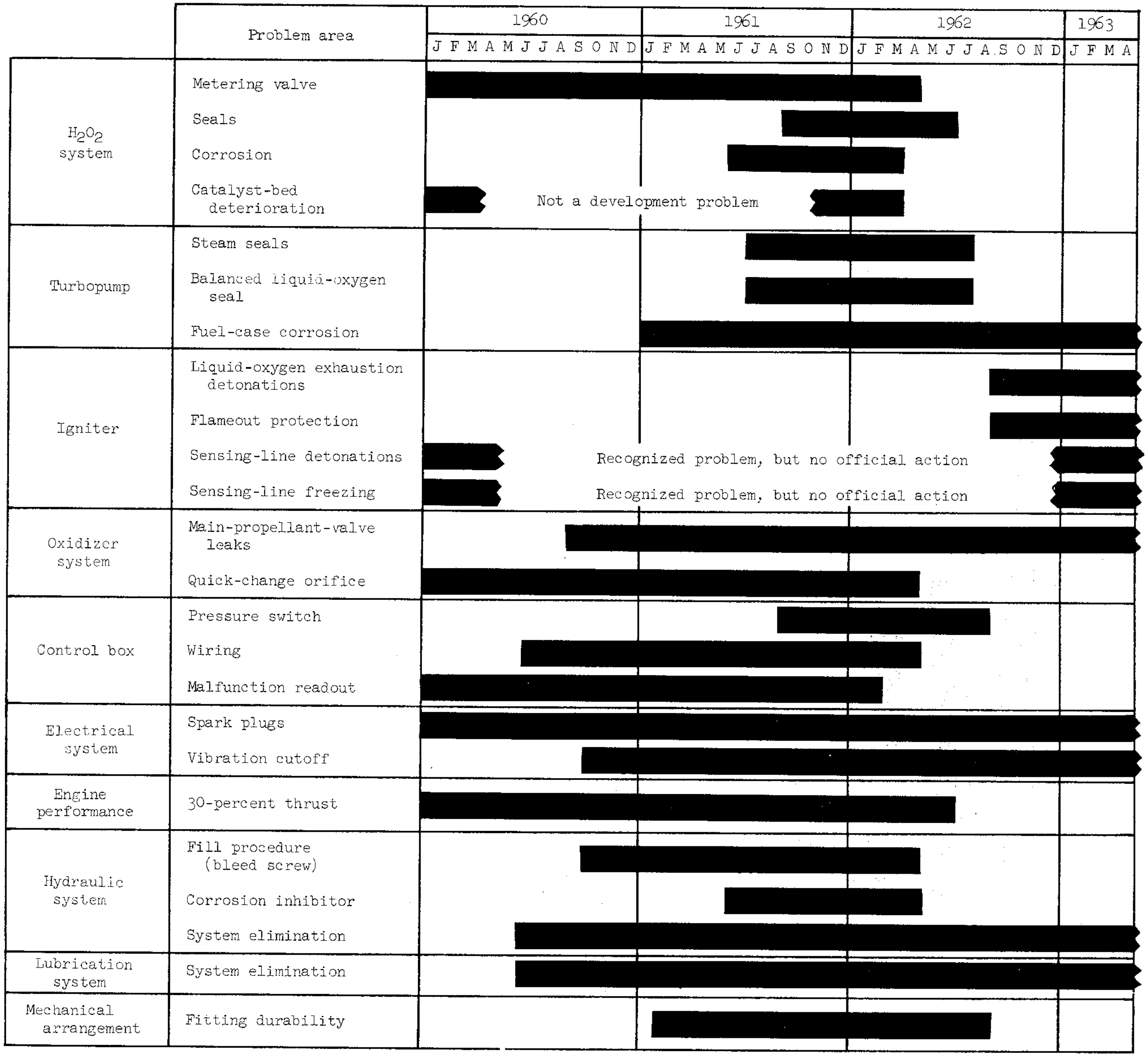


Figure 6.- Elapsed time from recognition to correction of major engine problems, including delays caused by lack of priority.

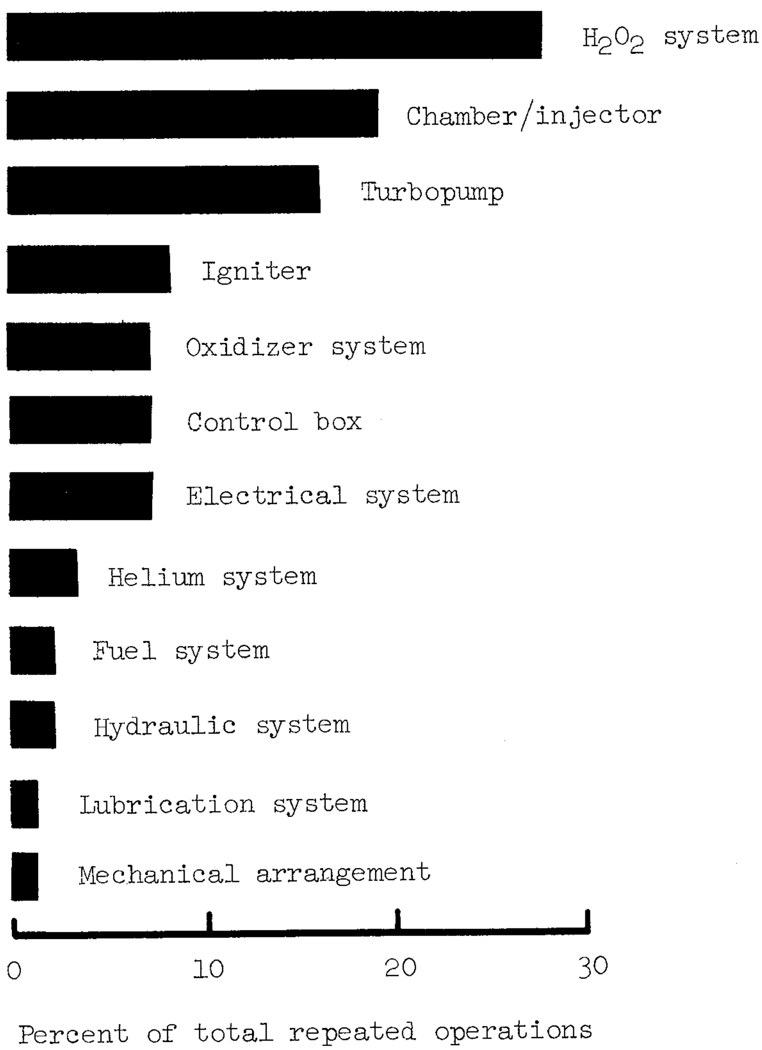
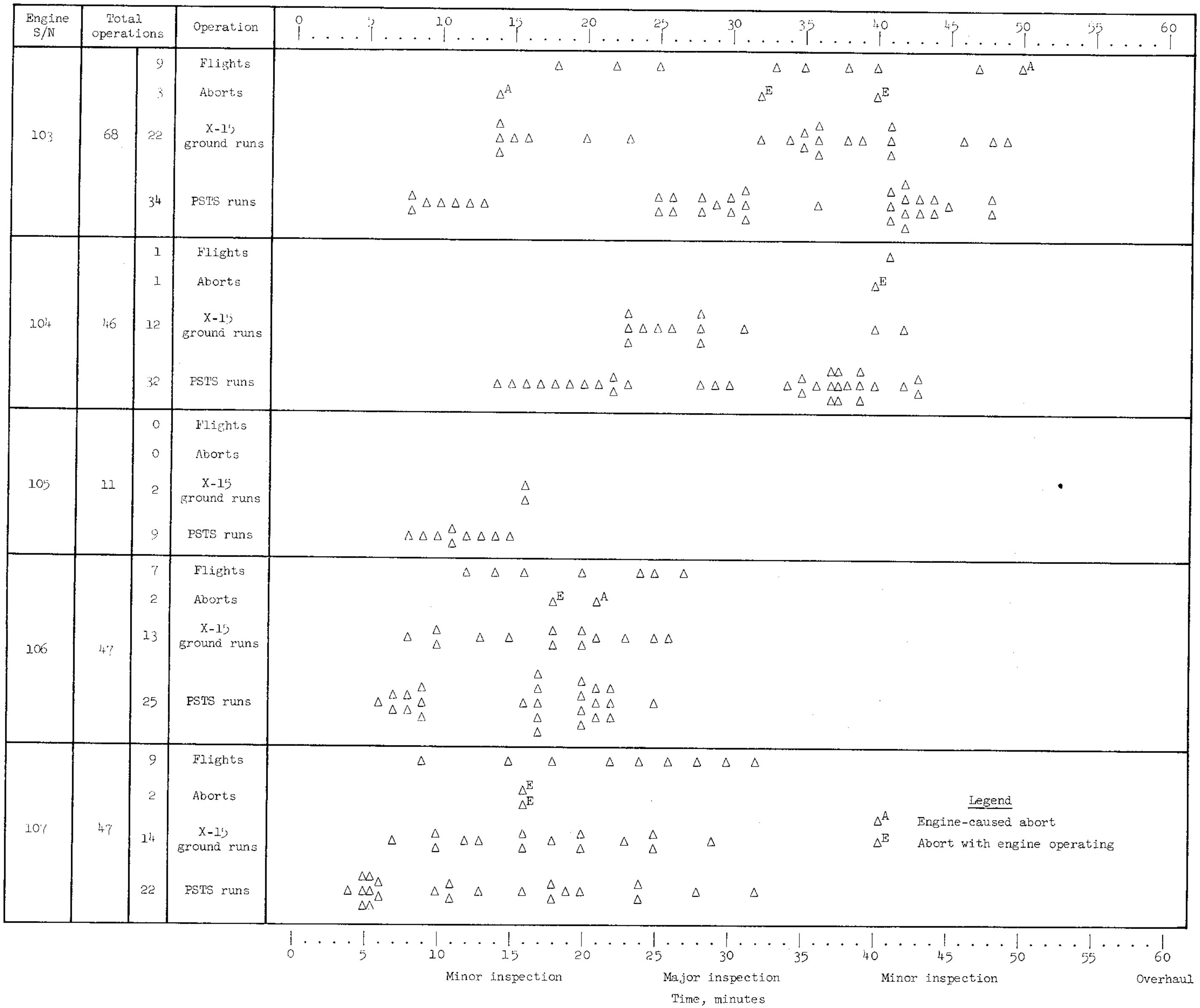
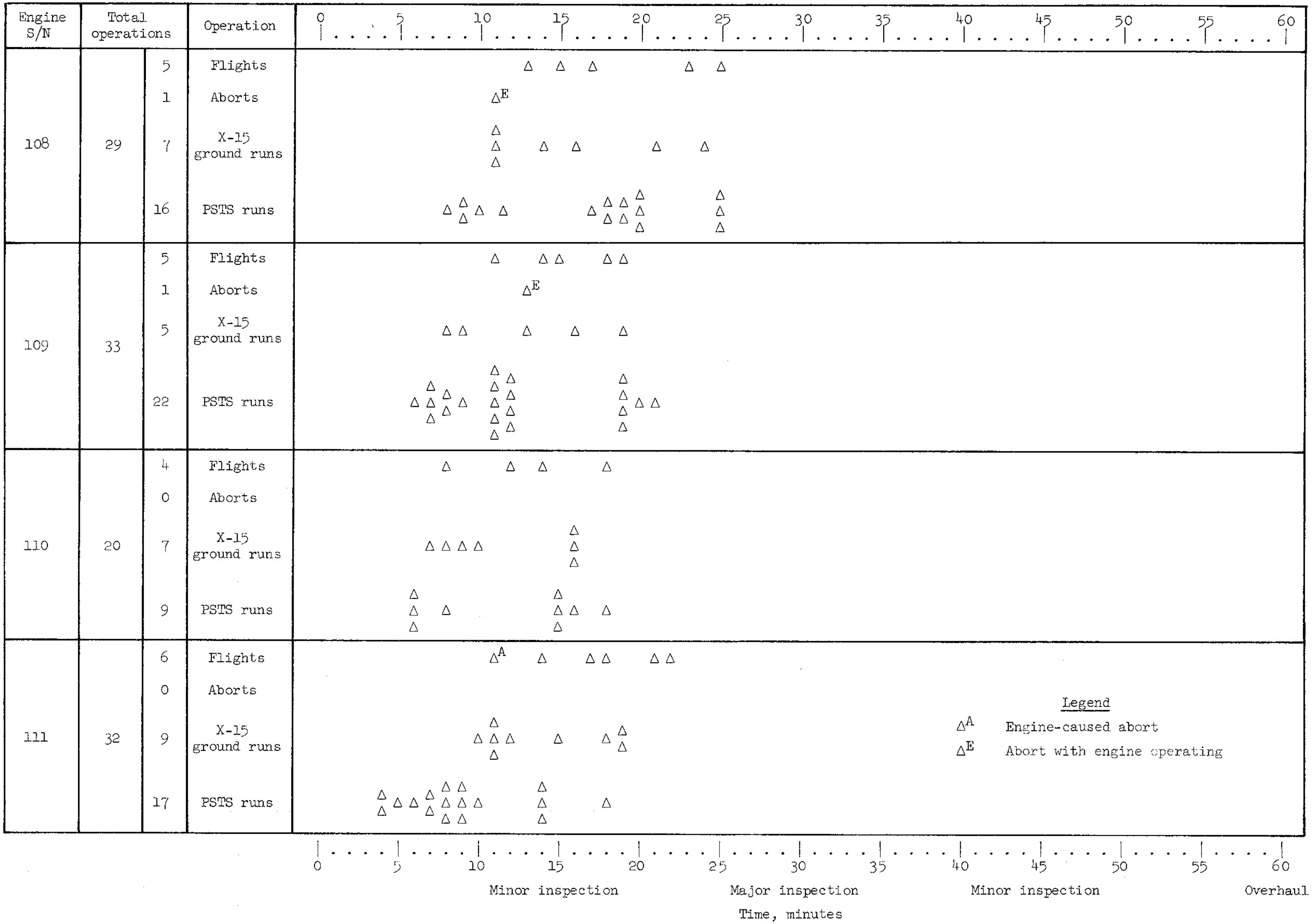


Figure 7.- YLR99 engine problems causing repeated operations.



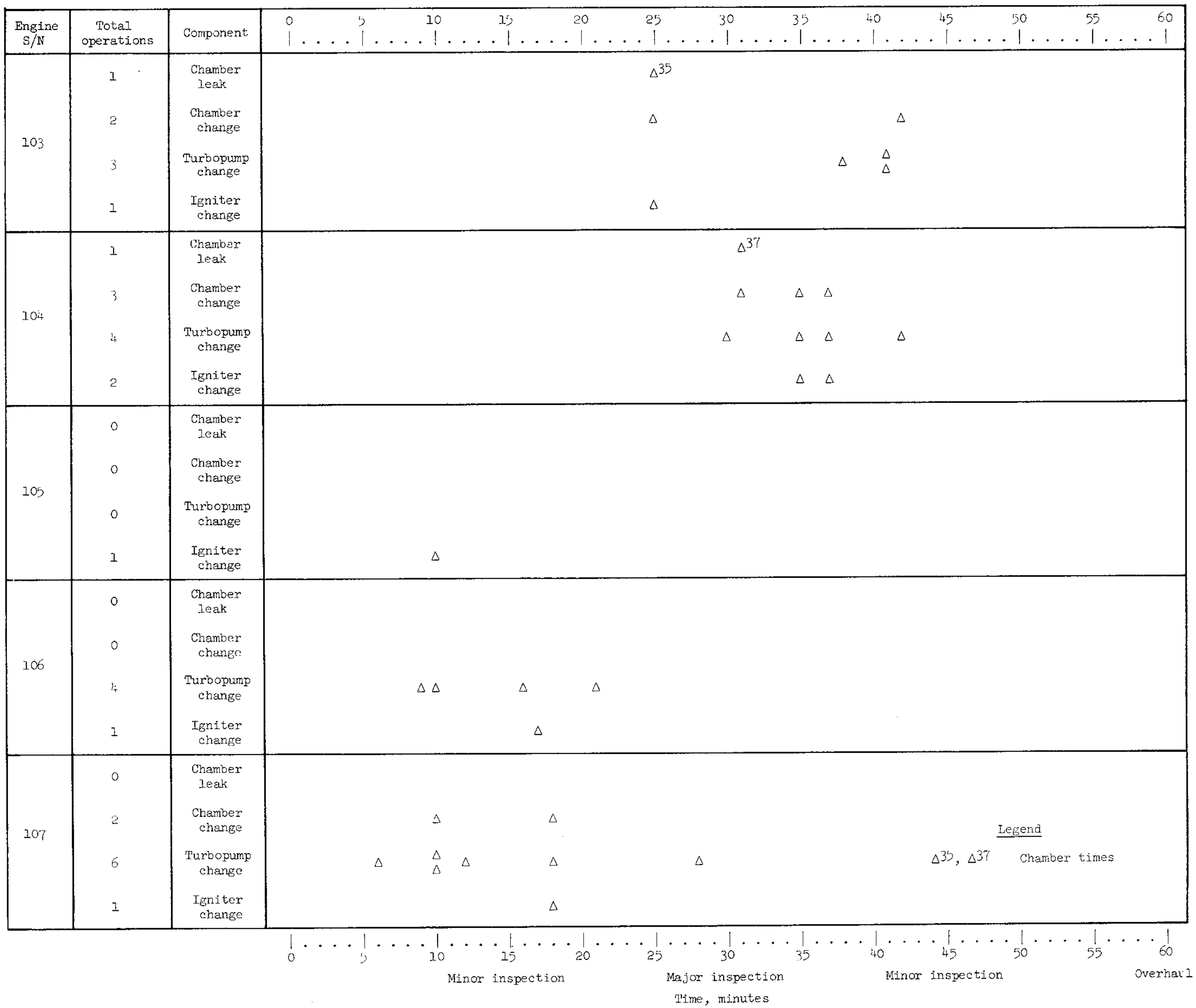
(a) Engine operations.

Figure 8.- YLR99 engine service life.



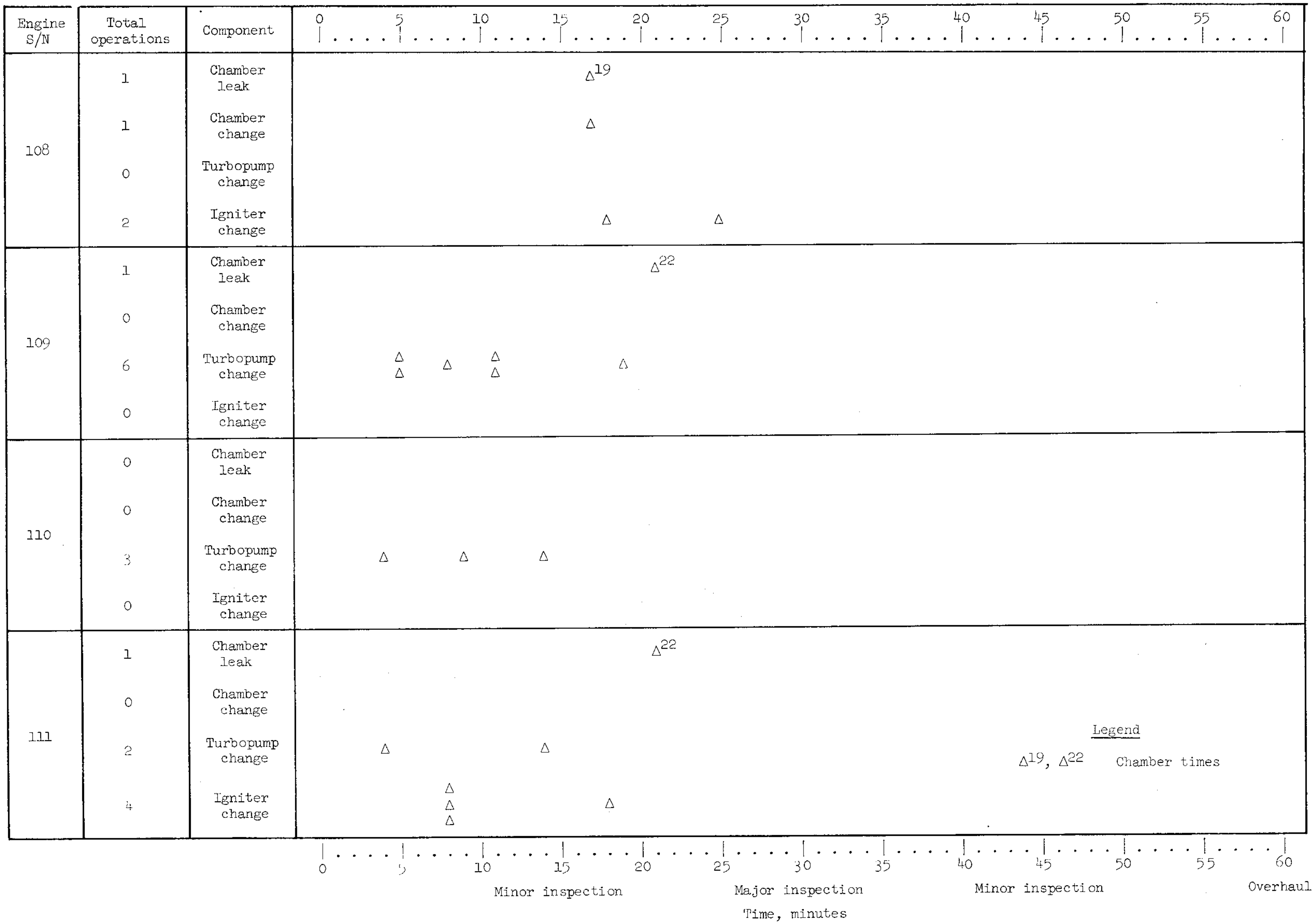
(a) Concluded.

Figure 8.- Continued.



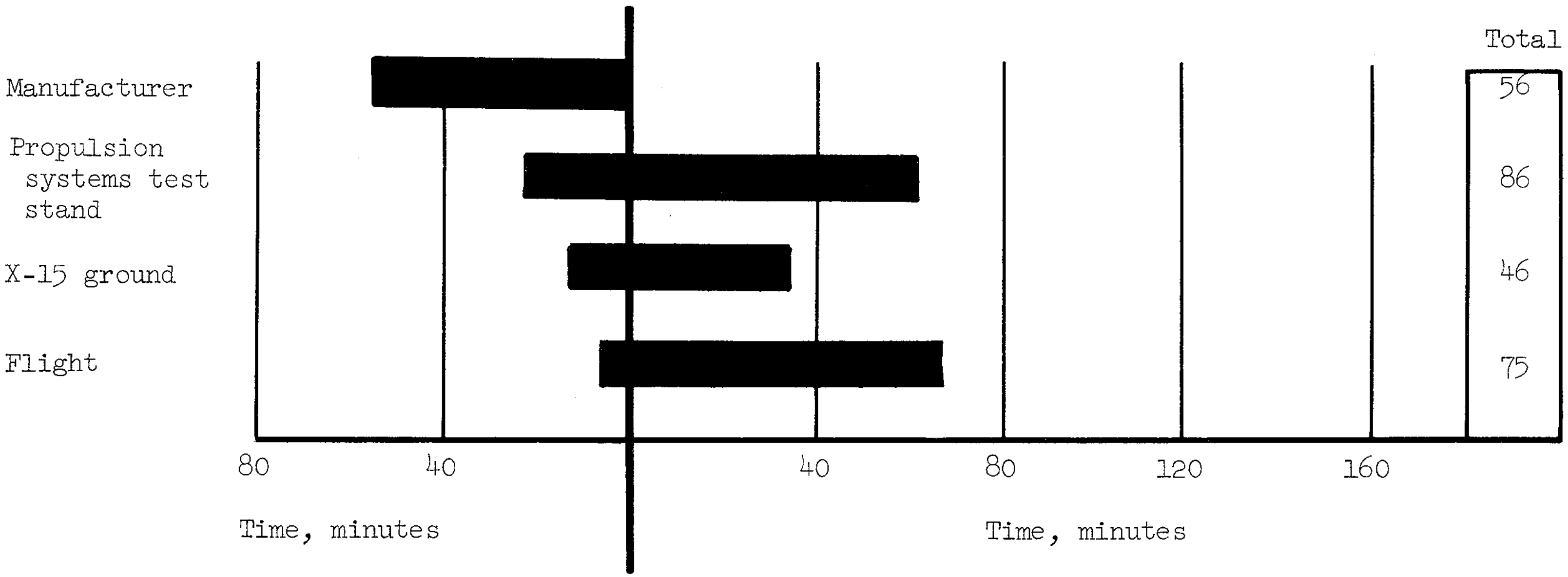
(b) Major component replacements.

Figure 8.- Continued.



(b) Concluded.

Figure 8.- Concluded.



Contractor operation - 3 flights. Government operation - 50 flights.

Figure 9.- Summary of YLR99 flight engine time.

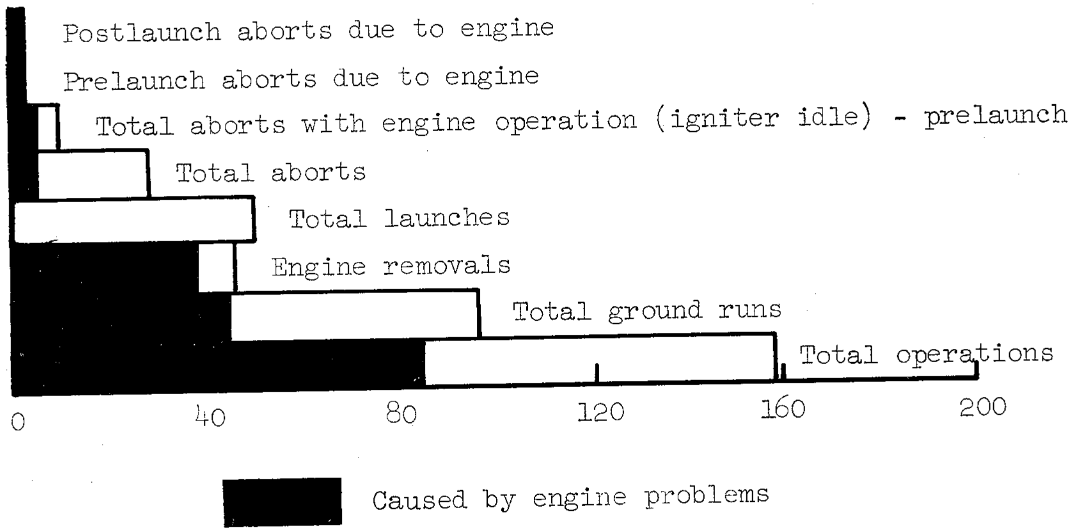


Figure 10.- Summary of YLR99 flight-engine operation in Government program.

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Problem areas, the effort involved in maintaining the engine in operational status, and the effect of the engine operations on the X-15 program are discussed. The data presented cover the first 50 Government flights with the engine installed in the X-15 airplanes. Engine modifications and several aspects of engine service life are described.

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